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MEASUREMENT OF ULTRASOUND ATTENUATION BY LASER-ULTRASONICS

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ABSTRACT

Laser-ultrasonics is a technique which uses lasers to generate
ınd detect ultrasound, and for which attenuation measurements are made
lifficult by the lack of precise knowledge of the laser beams
.ntensity distributions. We show that there are two cases where this
:nowledge is not generally required and where precise measurements can
›e performed.

Ultrasonic techniques are widely used for the determination of the elastic properties and the characterization of the microstructure of materials. The elastic constants are determined by the measurement of longitudinal and shear ultrasonic velocities [1]. The microstructure of the material (grain size, porosity, ...) is generally evaluated by measuring the attenuation of longitudinal or shear ultrasonic waves [2]. The traditional and generally used method for generating and detecting ultrasound is by piezoelectric transducers, which are either bonded to the specimen or use a fluid layer or a liquid column for ultrasonic coupling. Such a method is difficult to apply for characterization at elevated temperatures which is of a great practical interest since most ceramic and metal materials are processed at elevated temperature, and many of the new ceramic or ceramic-metal composites are used at elevated temperature.

Although buffer rods, cooling systems, special bonds or momentary contact have been used for laboratory characterization of materials at high temperature with conventionnal transducers, these solutions are not applicable to on-line industrial measurements. Electromagnetic transducers (EMATs) have been developped to solve this coupling problem, but these transducers have to be close to the surface (in the millimiter range). Furthermore all these techniques are difficult to apply when the surface has a varying curvature which occurs with many industrial components made of metal, ceramics or composites. All these problems are solved by laser-ultrasonics.

In the laser-ultrasonics technique, a pulsed laser generates ultrasound through thermal expansion at low laser power densities (thermoelastic effect) [3] or by vaporization of a small amount of surface material at high power densities (ablation effect) [3]. The generated ultrasonic wavefront follows the surface curvature, thus permitting to probe readily parts of complexe shape. The best sensitivity is obtained in the ablation regime, which produces longitudinal ultrasonic pulses with amplitude of the same order of magnitude as conventionnal transducers. This regime has the drawback to vaporize a small quantity of material at the surface, but in several cases of laboratory testing, this small surface damage of the order of a micron per hundred shots is acceptable. Strong longitudinal pulses are also produced in the damage-free thermoelastic regime by covering the surface with a transparent layer [4]. The acoustic source is in this case distributed underneath the surface and the stresses are essentially normal to the surface as in the ablation regime. The same effect is also observed without additionnal coating when the material absorbs weekly laser light. Laser-generated ultrasound is detected at the surface of the sample by a second laser coupled to an interferometer. The various interferometric techniques have been reviewed recently [5].

The laser-ultrasonic technique has been used to determine the elastic constants of metals and ceramics. at room and elevated temperature [6,7]. However, to our knowledge, the analysis of decreasing amplitude of the successive echoes, which will yield material attenuation and information on its microstructure, has not been so far reported, although in one case considered [8]. The reason comes from the fact that attenuation cannot be readily deduced from

echo height decrease, since this decrease should be corrected from diffraction effects coming from the finite sizes of the generating and receiving laser spots on the surface of the sample. Since many commercial lasers have intensity distributions which are not well defined, which are very sensitive to laser cavity alignment and which cannot be represented by analytical functions, diffraction effects cannot be precisely evaluated. This is further aggravated by local variation of surface absorption and reflectivity. However, as we show in this paper, there are at least two cases where the laser beam distribution and surface variations have negligible effects and precise ultrasonic attenuation measurement can be performed.

We consider only in this paper the cases where laser generation produces stresses essentially normal to the surface, and longitudinal waves. We show first theoretical results applicable to uniform generation and reception over zones of radius a (generation) and b (reception) and which are derived from reference 9. Data shown in figure 1 for a=b and a≠b gives the integrated displacement response over the spot radius b produced by a piston source of radius a versus the parameter $s=\lambda z/a2$, or $s=\lambda z/b2$ where λ is the acoustic wavelength and z is the distance between the receiving spot and the source. Reciprocity considerations show that the results are symmetric in a and b. For example the curve corresponding to b=4a is the same than the curve a=4b, except that the parameter s has to be $s=\lambda z/b2$ instead of $s=\lambda z/a2$. Figure 1 shows two cases of particular interest :

<u>case 1 : large s values</u>. As shown in figure 1, in the case of large s values, the amplitude decrease is independant of the relative sizes of the source and receiver spots. Large s values can be either obtained by small source and receiving spots, or a large distance z between generation and reception, or large ultrasonic wavelengthes , i.e. low ultrasonic frequencies. This case corresponds to the spherical wave approximation, in which the source and receiver can be considered as point-like compared to the ultrasonic wavelengths, and in which the amplitude decreases with the distance as 1/z. The diffraction loss in dB between two distances of observation z1 and z2 is therefore

(1) $D(w) = 20 \log (z1/z2)$.

In the case of a measurement in transmission on a sample of thickness h, the source and receiver are on opposite sides of the sample, z1=h and z2=3h, and the diffraction contribution is equal to D(w)=20log(1/3)=-9.54 dB. In the case of a measurement in reflexion, the source and receiver are on the same side of the sample, z1=2h and z2=4h, and the contribution of diffraction is equal to D(w)=20log(1/2)=-6.02dB.

<u>case 2 : small s values</u>. It can be seen from figure 1 that for small s values, the amplitude variation is small provided that the source and receiver spots are not too different in sizes. If the size ratio a/b of the source and receiver increases or decreases, the amplitude variation increases and shows an oscillating trend. Small s values corresponds either to large source or receiver spots, small distance z between source and receiver or measurements at high

frequency. This case corresponds to the plane wave approximation in which the amplitude decrease with the distance is small. The diffraction correction in this case can often be neglected, provided that the source and receiver have sizes of the same order of magnitude and that the attenuation to be measured is sufficiently large. Otherwise, in the case of source and receiver of very different sizes and small attenuation, the laser intensity distributions being not exactly known the diffraction correction cannot be evaluated and a measurement of attenuation is not possible. We present below experimental results which illustrate these two cases.

The first case is illustrated by data taken on a 6.38mm thick PZT ceramic sample. Ultrasound is generated in the ablation regime by a Q-switched Nd:YAG laser focused to a spot of ~0.5mm in diameter. An argon ion laser coupled to an heterodyne displacement interferometer described in reference [10] is used for detection at epicenter (on the opposite side of the sample in front of the generating spot). Optimum sensitivity of such an optical receiver is obtained when one optical speckle is detected [5] and accordingly, the argon ion laser beam is focused onto the specimen surface to a near diffraction limited spot of ~0.1mm in diameter. The displacement signal is first digitally sampled and processed to eliminate low frequency components by taking its derivative. The first two longitudinal pulses are then selected by a Blackmann-Harris window [11] which permits to minimize truncation effects. The two windowed data are then Fourier transformed and the total round trip loss including attenuation and diffraction is calculated and shown in figure 2.

In order to calculated the diffraction correction, we make use of figure 1 after noting that in this case a~5b. From figure 1, we find that the spherical wave approximation applies for s>30, which after taking into acccount sample thickness and acoustic velocity corresponds to frequencies below ~13MHz. We then make the 9.54dB frequency independant correction applicable to this case and obtain the diffraction corrected curve shown in figure 2. This curve is compared with results obtained by conventional piezoelectric transducers (only the fitted smooth curve is shown for sake of clarity). It can be seen that the agreement between both data is good (a variation in f2 is observed), except above 13MHz where the spherical wave condition is not satisfied and below 2MHz because of the error introduced by data truncation.

The second case is illustrated by data taken on a 7.36mm thick graphite-epoxy composite plate, in which ultrasound is generated in the thermoelastic regime by a pulsed CO2 TEA laser. This laser oscillates on transverse modes which give a non-uniform spot of 3x6mm with several more intense areas. The sample being coated with a thin film of paint partially transparent to the generating laser radiation, the generating stresses are buried and then produce essentially a longitudinal wave emitted perpendicularly to the surface. The receiving laser is the same argon ion laser as before, but unfocused and giving a spot of 6mm in diameter on top of the generating zone. The scattered light is coupled to a Fabry-Perot velocity interferometer described in reference [12]. Unlike the heterodyne displacement interferometer used previously, this system can detect

ultrasound over a large spot [5]. We use the same procedure as above :o calculate attenuation, omitting only the derivative step since this ›peration is performed by the receiving velocity interferometer. The :esults uncorrected of the diffraction effect are plotted in figure 3 ınd it can be seen that there are in good agreement with a iiffraction-corrected measurement obtained with a piezoelectric :ransducer and that they follow roughly a variation proportional to frequency. This means that the diffraction correction can be ıeglected in the frequency range of the measurement, i.e. 1.5MHz to 7MHz. In this range the s parameter, which is taken now as $s=\lambda z/b2$, aries between 3.25 and 0.7 at the distance z=2h (the acoustic elocity is 3100m/s) and between 6.5 and 1.4 at z=4h, while the ttenuation taken from figure 3 varies between 3.3dB and 14dB over the iistance 2h. If we assume that the generation zone is made of several iston sources of the order of 1mm in diameter, figure 1 (or more xactly the plot corresponding to b=3a not shown for clarity), gives a iffraction correction over the distance 2h of ~1.5dB at 1.5MHz and .75dB at 7MHz. The latter is obviously negligible whereas the former s about twice of what seems reasonable from the deviation observed in igure 3. This can be explained by the fact that the "hot" generation pots are actuallly elongated (3x1mm) and that there is also some nergy between them. This work shows that, in spite of the poor enerating laser beam quality, attenuation measurements can be made sing a large uniform receiving spot.

If a small receiving spot is used, the curve a=10b of figure 1 hows that the contribution of diffraction can be large. Actually, a easurement was performed in transmission with the laser heterodyne robe used in the first example and the results are plotted in figure . They show large deviations from the exact attenuation curve which re caused by diffraction effects.

In conclusion we have shown that laser-ultrasonic technique can e used to measure ultrasonic attenuation without accurate knowledge f the laser power distributions in two limit cases corresponding to he spherical wave and the plane wave approximations. In the first ase, the conditions of which are more easily met by focusing the asers, using thick samples and at low frequencies, the correction is requency independant and easily calculated. In the second case, the orrection is assumed to be zero and this case generally applies to arge spot sizes, thin samples and high frequencies. In this case, it s preferable to have the generating and receiving spots with similar izes. Both cases yield meaningful results only if the attenuation to e measured is sufficiently large, so that the small deviations of the orrections from their assumed constant value can be neglected.

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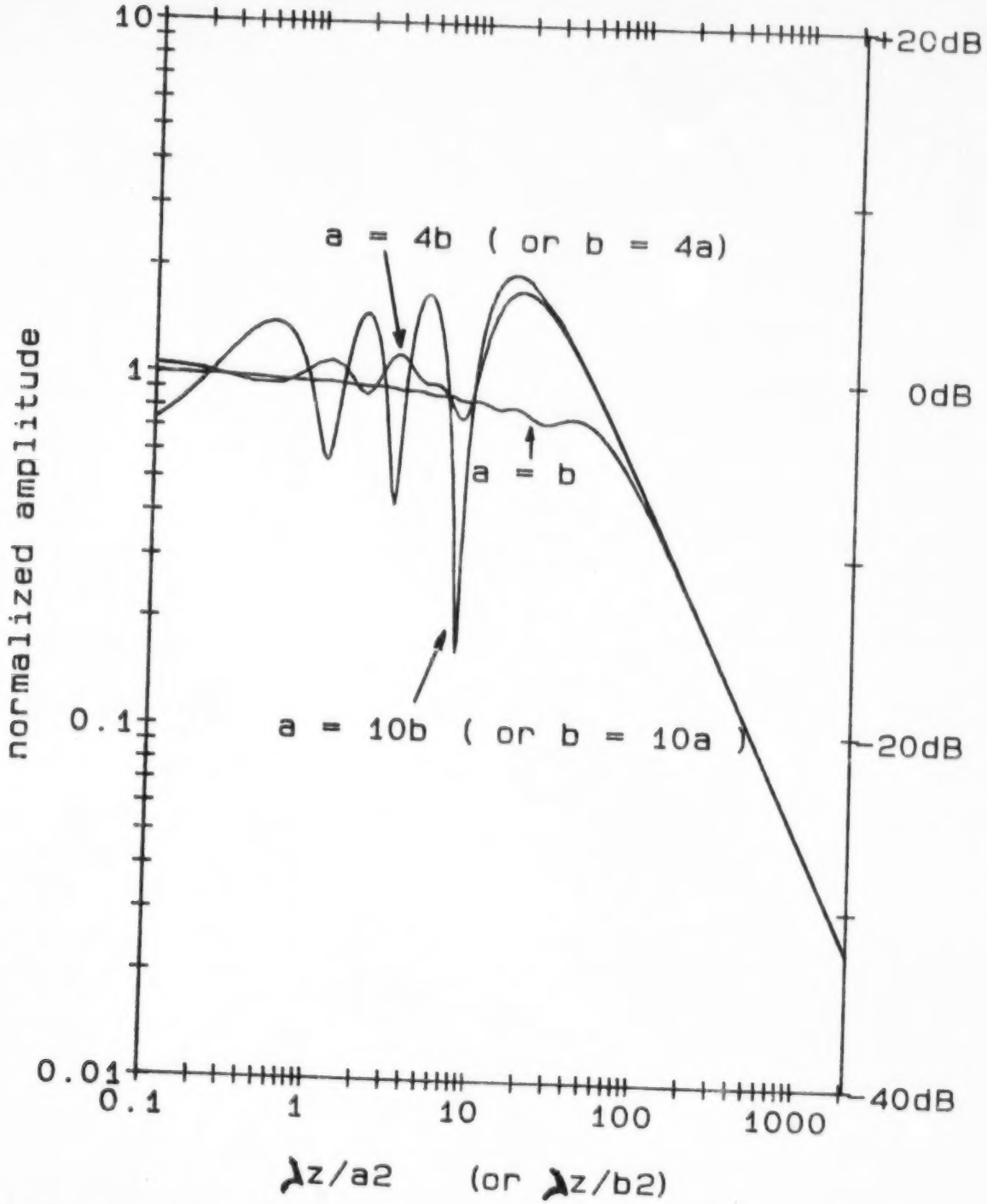

Figure 1 - Normalized amplitude of the integrated ultrasonic displacement versus the parameter s=λz/a2 for different values of the generating radius a and receiving radius b. Only 3 curves a=b, a=4b (or b=4a) and a=10b (or b=10a) are shown for sake of clarity.

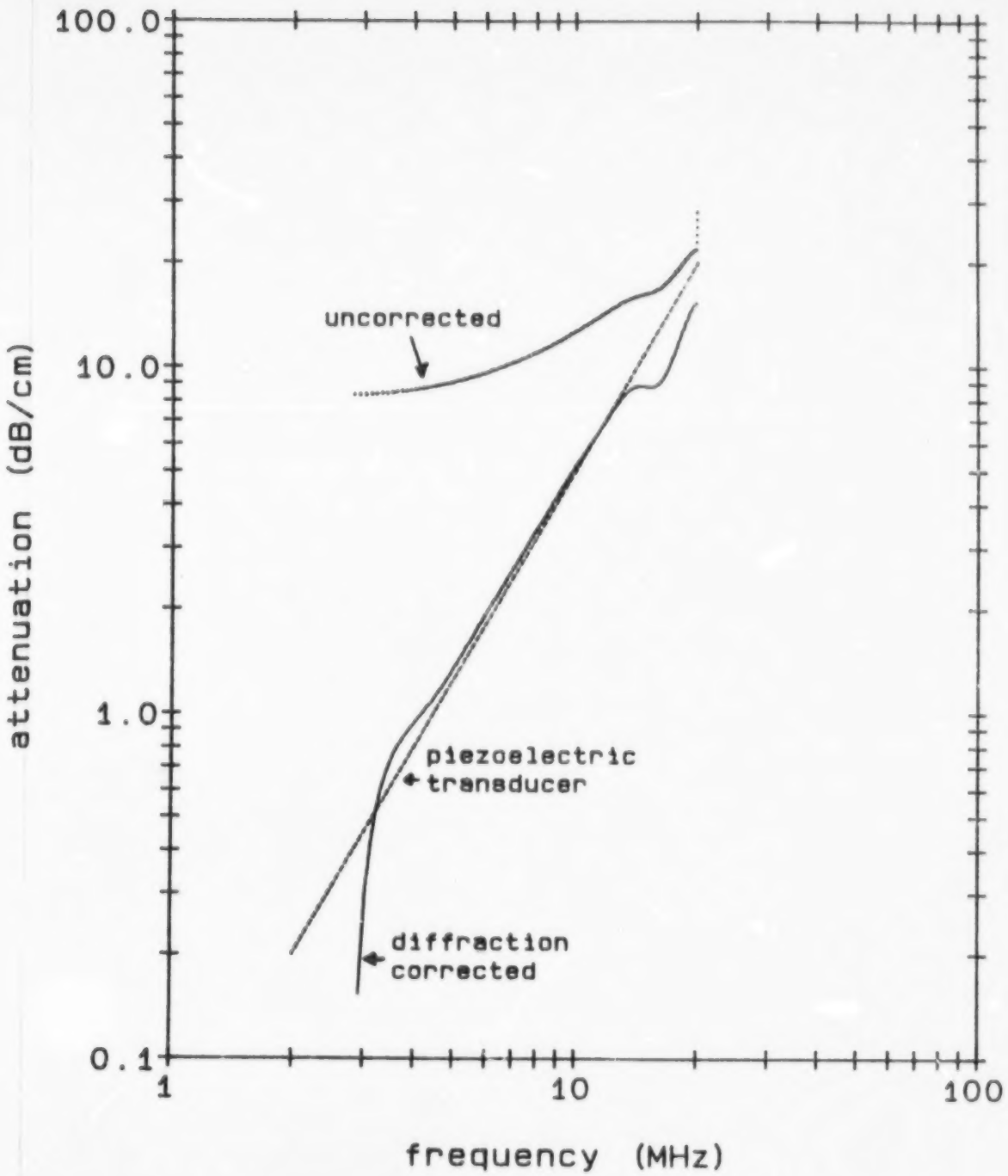

Figure 2 - Longitudinal ultrasonic attenuation measured by laser-ultrasonics on a PZT ceramic sample illustrating case 1 (spherical wave limit). The detecting sensor is a laser heterodyne interferometer. Also shown is the variation obtained with a piezoelectric transducer after diffraction correction and smoothing.

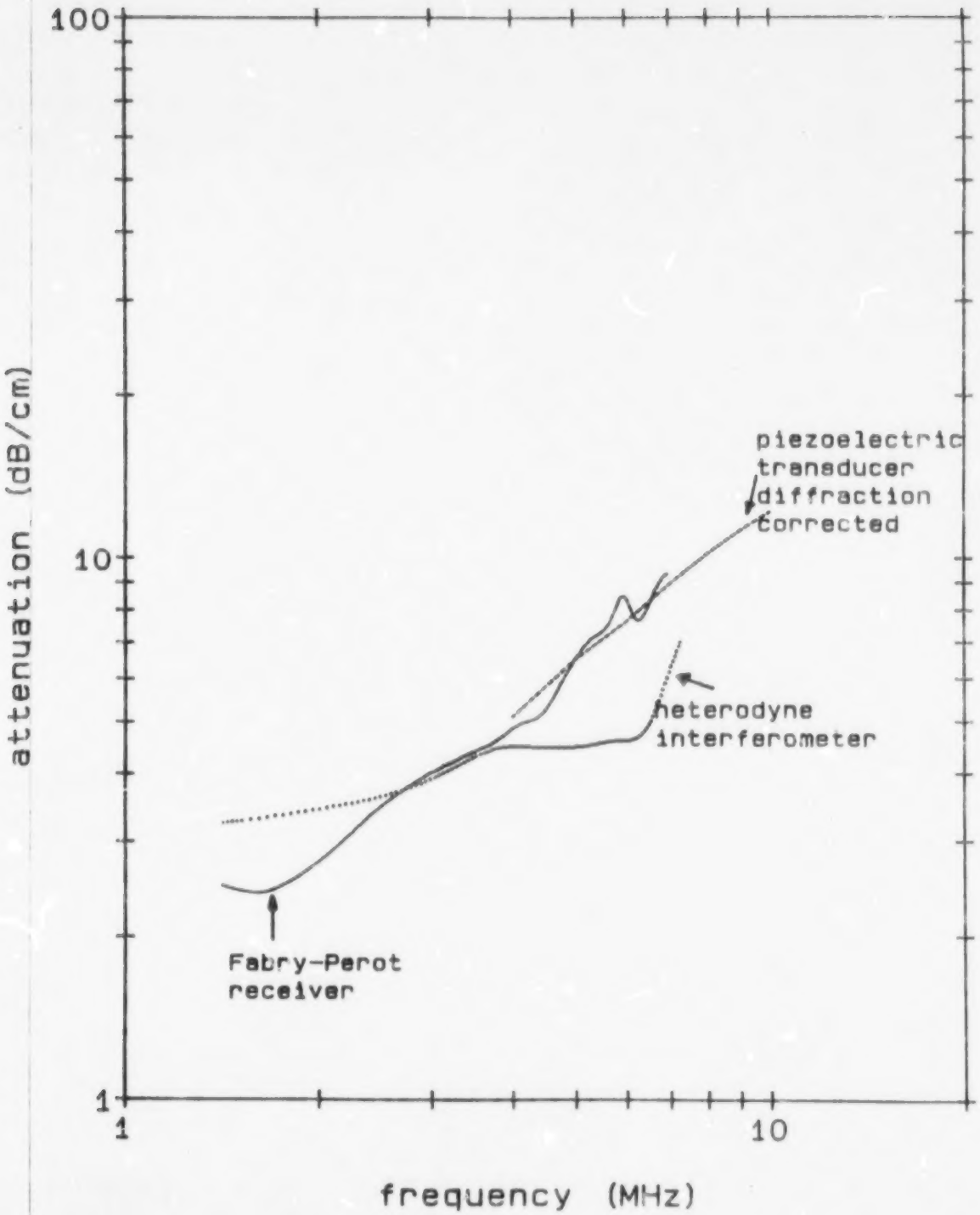

Figure 3 - Longitudinal ultrasonic attenuation of the graphite-epoxy sample measured by a conventionnal piezoelectric transducer, Fabry-Perot receiver and laser-heterodyne receiver.